SCIENTIFIC REPORT

Screening Environmental and Human Health Impacts of Natural Diamond Mining and Processing

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Division of Environmental Systems Analysis

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Cover:
The picture illustrates a rough natural diamond from mining and processing.

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Summary

Natural diamond, used in applications ranging from jewelry to machining tools, is the hardest material found in nature. The mining and processing of natural diamond is associated with substantial impacts on the environment as well as on human health. Large-scale diamond mining requires considerable amounts of energy and generates large amounts of tailings. About one fifth of the global diamond production originates from artisanal mining, which is associated with adverse human health impacts as the miners typically work under harsh conditions. Despite this, the environmental and human health impacts of natural diamond mining and processing have until now not been investigated to any depth. The aim of this study is to conduct a screening assessment of environmental and human health impacts of natural diamond production with an average global perspective. The method of life cycle assessment is applied, and the disability-adjusted life years indicator is used for the quantification of human health impacts. The results from this screening study shows that about 1.3 life days are lost per carat of natural diamond produced globally. This corresponds to a loss of about 490 000 life years considering the total global production at 134 million carats in 2016. The human health impact is clearly dominated by the contribution from occupational accidents in the artisanal diamond mining (97% of the total human health impact). Other sources of impacts, such as occupational accidents during the large-scale share of mining and processing, contribute with the remaining few percentages. The environmental impact results were, on the contrary, dominated by the use of electricity in large-scale mining and processing. The results from this study can be applied in future life cycle assessments of natural diamond and related end products. A sensitivity analysis identified parameters such as the number of artisanal miners and the annual fatal accident rate in artisanal mining in need of being further investigated in further studies. In addition, a more detailed assessment of large-scale mining and processing and the development of a method to include also positive human health impacts to artisanal miners are recommended.

Keywords: Diamond; Life Cycle Assessment (LCA); Disability-adjusted life years (DALY); Artisanal mining; the Democratic Republic of the Congo (DRC)

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Contents

1 Introduction

Natural diamond, which is formed deep down in the Earth's crust at extreme pressures and temperatures, is the hardest known material in nature (Kreuger, 2010). In contrast to human-made diamond, or so-called synthetic diamond, which was invented in the 1950s, the natural diamonds mined today have been formed for billions of years (Gupta, 2018). Natural diamond was first discovered around 4000 BC in India, which dominated the diamond production globally until the 18th century when the Indian diamond mines became exhausted (Kreuger, 2010). In more recent times, a number of countries are responsible for the majority of the global natural diamond production, including Russia, the Democratic Republic of the Congo (DRC), Botswana, Australia and Canada. The worldwide production of rough natural diamond, i.e. uncut natural diamond, was about 27 metric tons in 2016 and had a value of $15.4 billion (USGS, 2020). These diamonds are either used as gemstones (55% in 2016) or for other industrial purposes (45%) (USGS, 2020), such as in grinding, cutting and drilling operations (Kreuger, 2010).

While natural diamond is a high-valued material with applications ranging from jewelry to machining tools, it is also associated with substantial negative impacts on the environment and on human health. Large-scale, or industrial, natural diamond mining and processing requires considerable amounts of energy (Ali, 2017) and generates large amounts of tailings (Marinescu et al., 2016). Artisanal mining, which implies that miners work under very harsh conditions with rudimentary tools and techniques, is associated with severe human health impacts but also adverse impacts on the environment (IGF, 2017). As much as about one fifth of the natural diamond production globally is from artisanal mining and processing (USGS, 2020). In addition, conflict diamonds, i.e. artisanal mining of diamond in weak states such as the DRC, is also associated with negative impacts on human health, for example when miners fall prey to armed groups (Van Bockstael, 2018; Vlassenroot and Van Bockstael, 2008). Thus, there are clear indications of significant environmental and human health impacts associated with natural diamond mining and processing. However, to date, no assessment of these impacts has been conducted.

Life cycle assessment (LCA) is the most well-developed tool for assessing impacts of products (Ness et al., 2007; Finnveden et al., 2009), and is commonly used to identify life-cycle impact "hotspots", i.e. the largest contributors to different impacts in terms of processes, emissions and resource use (Hauschild et al., 2018). Previously, an LCA of synthetic diamond produced via high-pressure high-temperature apparatuses has been conducted (Furberg et al., 2020b) and some early insights on human health impacts of natural diamond have been presented (Furberg et al., 2020a). However, an LCA of the environmental and human health impacts of natural diamond mining and processing has not been conducted. The aim of this study is to assess environmental and human health impacts associated with natural diamond by conducting a screening LCA of natural diamond mining and processing with an average global perspective.

2 Method

This study is a cradle-to-gate LCA, implying that environmental impacts are assessed from raw material extraction over to the production of rough natural diamond (Baumann and Tillman, 2004). It is furthermore an attributional LCA, meaning that the environmental impacts associated with the product system, rather than impacts associated with changes in the product system, are assessed (Finnveden et al., 2009). The study is conducted in accordance with the ISO 14040 standard for LCA (ISO, 2006). The modelling was conducted using the OpenLCA software version 1.10.3 (GreenDelta, 2020b) together with the OpenLCA life cycle impact assessment (LCIA) method package version 2.0.5 (GreenDelta, 2020a). More information on the specific LCIA methods applied in this study are provided in Section 2.3.

2.1 Functional unit

The functional unit was set to be 1 carat, which is equal to 0.2 g, of rough natural diamond. Specifically, the functional unit represents 1 carat of global average rough natural diamond, where a certain share originates from large-scale mining and the remainder from artisanal mining. The global natural diamond production was operationalized by applying data from USGS (2020) for the year 2016. In that year, about 83% of the global natural diamond production were from large-scale production while the rest were produced in the DRC, mainly from artisanal mining. Thus, for the functional unit of 1 carat natural diamond produced globally, 0.83 carat is from large-scale diamond mining and processing while the remaining 0.17 carat is from artisanal diamond mining and processing in the DRC.

2.2 System studied

The studied system of global diamond production involves both large-scale and artisanal mining and processing (Figure 1). The large-scale mining and processing in a limited number of countries, including Russia, Botswana, Australia and Canada, are responsible for a significant share of the global natural diamond production (USGS, 2020). In total, these four countries contributed with about 65% of this production in 2016 (Figure 2). In addition, almost one fifth of the global production originates from the DRC, where the majority of the diamond mining is artisanal (USGS, 2020) (Figure 2). More specifically, Van Bockstael (2018) stated that 100% of the diamond produced in the DRC is from artisanal mining and processing. Although artisanal diamond mining and processing also takes place in other countries, such as Lesotho and Ghana (Makhetha and Maliehe, 2020), this production only contributes with a minor share of the total global production according to the USGS (2020). Thus, in this study, artisanal mining was only assumed to take place in the DRC. The large-scale mining and processing, on the other hand, were modelled by applying global data, e.g. a global electricity mixture was assumed for inputs of electricity. Allocation by cut-off was applied in waste treatment, meaning that recycled materials are only responsible for their direct impacts (Ekvall and Tillman, 1997). Furthermore, capital goods were not included in the assessment.

The various contributions to human health impacts from global natural diamond mining and processing that were included in this study are shown in Figure 1. Impacts on human health from emissions in the production system of large-scale diamond mining and processing were included (see further Section 3.2.1). Occupational accidents in the production system of large-scale diamond mining and processing were included (see further Section 3.2.2). Occupational accidents in artisanal diamond mining and processing in the DRC, where miners work under harsh conditions applying rudimentary tools and techniques, were assessed (see further Section 3.2.3). In addition, impacts associated with the fact that the mining and trade of diamonds in the DRC is contributing to the ongoing conflict in the area were also included (see further Section 3.2.4).

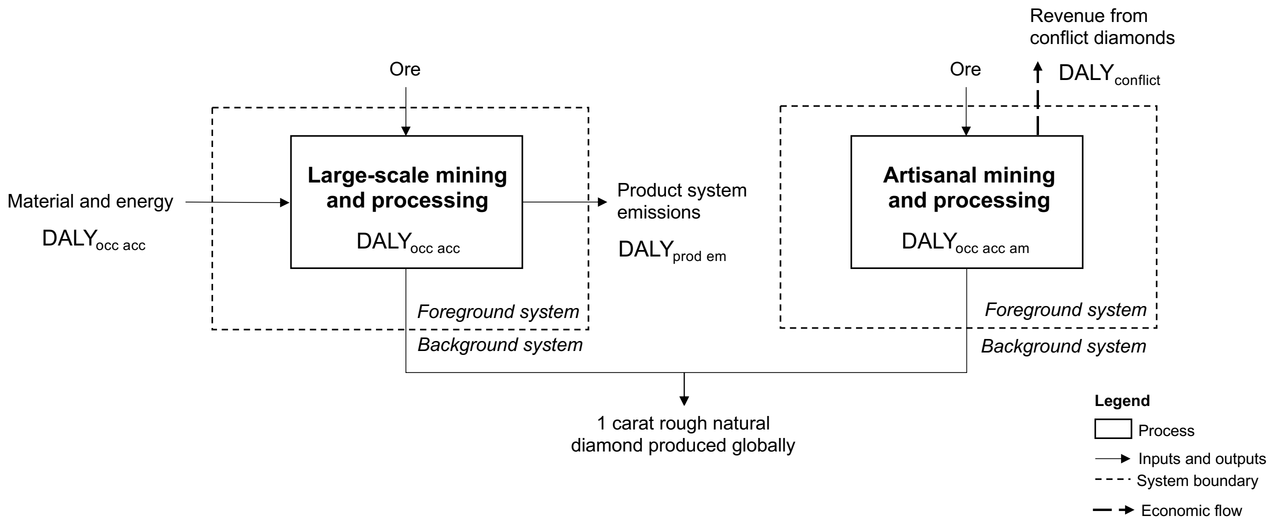

Figure 1. Flowchart for the studied system of global natural diamond production, including both large-scale and artisanal mining and processing. The foreground and the background system as well as the functional unit, being 1 carat natural diamond produced globally (i.e. 0.83 carat from large-scale production and 0.17 carat from artisanal mining in the DRC) is also indicated. $DALY_{prod\ em}$ = years lost due to large-scale diamond production system emissions, $DALY_{occ\ acc}$ = years lost due to occupational accidents in the production system of large-scale diamond mining and processing, $DALY_{occ\ acc\ am}$ = years lost due to occupational accidents in artisanal diamond mining and processing and $DALY_{conflict}$ = years lost due to the conflict associated with artisanal diamond mining and processing in the DRC

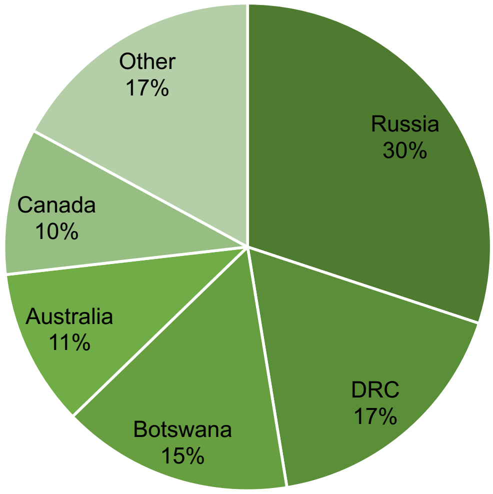

Figure 2. The share of the global production of rough natural diamond in various countries in 2016 (USGS, 2020). The total global production in 2016 was 134 million carats, which equals about 27 metric ton. DRC=the Democratic Republic of the Congo

2.3 Impact assessment

Environmental impacts were assessed for four different midpoint indicators: climate change [kg CO_2 eq], freshwater eutrophication [kg P eq], terrestrial acidification [kg SO_2 eq] and stratospheric ozone depletion [kg CFC11 eq]. These were selected to represent a broad range of environmental impacts. The LCIA method of ReCiPe version 2016 with the hierarchist perspective (Huijbregts et al., 2017), was applied for the assessment. This perspective implies that scientific consensus regarding time frames and plausibility constitutes the foundation for the modelling of impact mechanisms (Huijbregts et al., 2016).

Human health impacts were modelled by applying the endpoint indicator of disability-adjusted life years (DALY), which is a measure for the life years lost due to premature death and disability. This measure, which was developed for the World Bank and the World Health Organization in the 1990s (Murray and Lopez, 1996), is commonly applied in global burden of disease studies, see e.g. Abajobir et al. (2017). It has also been used to assess human health impacts in LCA studies of various products, such as an airbag system, a catalytic converter, gold jewelry (Arvidsson et al., 2018), a nano-enabled chemical gas sensor (Gilbertson et al., 2014) and tire studs (Furberg et al., 2018a). DALY is calculated as the sum of the years lost due to premature death (YLL) and the years lost due to disability (YLD), which are calculated according to:

$$YLL = N \times (LEX - L) \qquad \text{Eq. 1}$$

$$YLD = \sum_{p} I_p \times DW_p \times L_p \qquad \text{Eq. 2}$$

where N is the number of deaths [-], LEX is the life expectancy [years], L is the age at death [years], I_p is the number of incidences of disability of type p [-], DW_p is the disability weight for the disability of type p [-] and L_p is the time spent with disability p until recovery or death [years].

Various methods were applied to quantify the different contributions to the human health impacts illustrated in Figure 1. The ReCiPe version 2016 method with the hierarchist perspective (Huijbregts et al., 2017) was applied to assess human health impacts of product system emissions, e.g. how greenhouse gas emissions by their contribution to climate change results in premature deaths and disability due to increased risks for diseases. Occupational accidents in the life cycle of large-scale diamond mining and processing was assessed by applying industry-level work environment characterization factors provided by Scanlon et al. (2014). These factors were based on US health and safety data as well as related quantities of industrial outputs. Occupational accidents in artisanal mining and processing of diamond, on the other hand, was assessed using various data from the literature, which was selected to represent artisanal mining in the DRC, specifically. This was done since the data provided by Scanlon et al. (2014), being based on US health and safety data, most probably does not adequately represent artisanal mining and processing in the DRC. Results for the years lost per kg of diamond mined in the DRC from Furberg et al. (2018b) was applied to quantify human health impacts related to the fact that mining and trade of diamond contributes to the ongoing conflict in the DRC. More details on the assessment of these different contributions to human health impacts in global natural diamond production are provided in Section 3.2.

2.4 Foreground and background system data

Data for the foreground system, as shown in Figure 1, were gathered through a literature search of mainly peer-reviewed articles but also other sources of information, such as reports. This data is described in Section 3. Data for the background system shown in Figure 1 were obtained from the Ecoinvent database version 3.7 (2020), using the “allocation, cut-off by classification” system model. The background system data were selected to be representative for global production, see Table A3 in the Appendix.

2.5 Sensitivity analysis

A sensitivity analysis was conducted in order to assess parameter uncertainties. Importantly, this was done in order to identify parameters in need of being further investigated in future studies. Parameter values were altered one at a time and resulting changes in environmental and human health impacts relative to baseline values were identified. Specifically, changes in (i) the results for the four included impact categories (climate change, freshwater eutrophication, terrestrial acidification and stratospheric ozone depletion) for environmental impacts and in (ii) the results for the total number of years lost due to the production of one carat natural diamond globally were assessed. All parameter values applied in the sensitivity analysis are presented in Table A1 and Table A2 in the Appendix.

3 Calculations

The calculations of environmental and human health impacts associated with the production of one carat natural diamond globally are described in Section 3.1 and 3.2, respectively. Data for the calculations were obtained from a literature search and baseline values were selected as the average value when parameters ranges were provided, unless a specific average value within this range was stated in literature. The value ranges for the parameters were tested in the sensitivity analysis. The data applied in the calculations, including the sensitivity analysis, are presented in Table A1 and Table A2 in the Appendix.

3.1 Environmental impacts of global natural diamond production

The environmental impact per functional unit for different impact categories was calculated according to:

$$I_i=(1-s)\times I_{LSM,\ i}+s\times I_{AM,\ i} \qquad \text{Eq. 3}$$

where I_i is the impact for impact category i per functional unit [e.g. kg CO_2 eq/carat], s is the share of the global natural diamond production that is from artisanal mining and processing [-], $I_{LSM,\ i}$ is the impact for i per carat natural diamond produced via large-scale mining and processing [e.g. kg CO_2 eq/carat] and $I_{AM,\ i}$ is the impact for i per carat natural diamond produced via artisanal mining and processing [e.g. kg CO_2 eq/carat]. Since about 17% of the global diamond production originated from artisanal mining in the DRC in 2016 (USGS, 2020), s was set to 0.17. Thus, I_i represents the impact for i of global natural diamond production, where about 0.83 carat is from large-scale mining and processing and 0.17 carat is from artisanal mining and processing in the DRC (see further Section 2.1).

3.1.1 Large-scale diamond mining and processing

Large-scale diamond mining and processing typically involves four main steps (Popplewell, 2019). First, in order to liberate the diamonds from the ore, the ore is crushed and then scrubbed to remove clay materials. Second, a diamond fraction is separated from the ore by the utilization of dense-medium separation cyclones. The fraction containing diamonds typically only constitutes a very small share of the feed to the cyclones, usually less than 1% by mass. Third, the diamond fraction is further treated to recover diamonds while the other fraction containing tailings becomes discarded to landfill. Diamonds are retrieved by X-ray fluorescence technology and by the use of petroleum grease tables. Fourth, and lastly, the retrieved diamonds from the previous step are cleaned by the utilization of acids and bases. The size range of the natural diamond output is commonly 1-25 mm.

The foreground system for large-scale mining and processing (Figure 1) comprises the materials and energy inputs to this process, as well as outputs of waste and emissions from this process. According to Ali (2017), information on energy use in diamond mining and processing can give a first indication of the associated impacts. This screening study is limited to major inputs, i.e. the inputs of energy and fuel, and outputs, i.e. tailings to landfill, in the modelling of the foreground system of large-scale mining and processing. The electricity and fuel consumption in large-scale diamond mining and processing was reported to be 7.5-80 kWh/carat and 1.9-5.2 kg diesel/carat, respectively (Ali, 2017). This consumption is highly dependent on the location of the mine, which also affects the type of energy sources behind the electricity consumption. For example, the electricity consumed at the Diavik mine, which is situated in Canada far away from other power sources, has to be generated onsite from diesel fuel (Ali, 2017). Regarding the generation of tailings, the concentration of diamond in good deposits might be less than 0.2 ppm (Popplewell, 2019) and on average 13 million ton of ore must be processed in order to produce 1 ton of diamonds (Marinescu et al., 2016). Thus, in total about 2 600 kg of tailings, which contains non-sulfidic minerals (Meyer and Seal, 1998), become generated and landfilled per carat diamond.

3.1.2 Artisanal diamond mining and processing

Artisanal and small-scale mining relies on unskilled workforces, which apply rudimentary tools and techniques (IGF, 2017). These activities are furthermore in general associated with adverse environmental impacts, including air and water pollution, deforestation and land degradation. Contemporary practices in artisanal diamond mining and processing, specifically, involves manual work by digging for ore, employing tools such as shovels and buckets, taking the ore out of the pit and then washing and sieving it for diamonds (Makhetha and Maliehe, 2020). Since artisanal diamond mining and processing typically relies on manual work, rather than the inputs of for example electricity and fuel, significant contributions to air and water pollution were not considered to be expected. Due to this, environmental impacts from air and water pollution related to artisanal diamond mining and processing were not included in this study. Note that the indicated use of water for the process of washing diamonds (Makhetha and Maliehe, 2020), was not included since it is difficult to know how much water that is used in this process and since it furthermore was not included for large-scale mining and processing (Section 3.1.1). When it comes to other types of environmental impacts, on the other hand, the search for diamond ore and the continuous pitting and trenching in artisanal diamond mining are associated with severe deforestation and land transformation (Aryee et al., 2003; Makhetha and Maliehe, 2020). Such impacts, however, are quite difficult to assess and were not included in this screening assessment, which was limited to the environmental impact categories presented in Section 2.3. Thus, $I_{AM,\,i}$ in Eq. 3 was set to zero in this screening study.

3.2 Human health impacts of global natural diamond production

Human health impacts per functional unit were calculated according to:

$$\begin{gathered}\mathrm{DALY}_{\mathrm{global\ diamond}}=(1-\mathrm{s})\times(\mathrm{DALY}_{\mathrm{prod\ em}}+\mathrm{DALY}_{\mathrm{occ\ acc}})+\\+\mathrm{s}\times(\mathrm{DALY}_{\mathrm{occ\ acc\ am}}+\mathrm{DALY}_{\mathrm{conflict}})\end{gathered} \quad \text{Eq. 4}$$

where $DALY_{global\ diamond}$ is the years lost due to the production of one carat natural diamond globally [years/carat], s is again the share of global natural diamond production that is from artisanal mining and processing [-], $DALY_{prod\ em}$ is the years lost due to emissions in the product system of large-scale natural diamond mining and processing [years/carat], $DALY_{occ\ acc}$ is the years lost due to occupational accidents in the production system of large-scale diamond mining and processing [years/carat], $DALY_{occ\ acc\ am}$ is the years lost due to occupational accidents in artisanal diamond mining and processing in the DRC [years/carat] and $DALY_{conflict}$ is the years lost due to the conflict associated with artisanal diamond mining and processing in the DRC [years/carat]. Thus, $DALY_{global\ diamond}$ represents the total lives lost for one carat global natural diamond where about 0.83 carat is from large-scale mining and processing and 0.17 carat is from artisanal mining and processing in the DRC (see further Section 2.1).

3.2.1 Emissions in large-scale mining and processing

The human health impact associated with production system emissions in large-scale mining and processing was calculated according to:

$$DALY_{prod\ em} = \sum_{j} CF_j \times I_j \qquad \text{Eq. 5}$$

where CF_j is the endpoint characterization factor for midpoint impact category j [e.g. years/kg CO_2 eq] and I_j is the life cycle's contribution to j [e.g. kg CO_2 eq/carat]. Since environmental impacts of artisanal diamond mining and processing were not included in this screening study (see Section 3.1.2), i.e. $I_{AM,\, i}$ was set equal to zero, I_j in Eq. 5 is equal to $I_{LSM,\, i}$ in Eq. 3. Thus, I_j is based on the data that is described in Section 3.1.1. The calculations of $DALY_{prod\ em}$ were done by applying the ReCiPe method, version 2016, with the hierarchist perspective (Huijbregts et al., 2017). In total, eight different midpoint impact categories contribute to human health impacts, namely fine particulate matter formation [kg PM2.5 eq], photochemical oxidant formation: human health [kg NOx eq], ionizing radiation [kBq Co-60 eq], ozone depletion [kg CFC-11 eq], human toxicity: cancer [kg 1,4-DCB eq], human toxicity: non-cancer [kg 1,4-DCB eq], climate change [kg CO_2 eq] and water use [m^3 water eq consumed].

3.2.2 Occupational accidents in large-scale mining and processing

Occupational accidents in the life cycle of large-scale diamond mining and processing were calculated according to:

$$DALY_{occ\ acc} = \sum_{k} CF_{WE,\, k} \times m_k \qquad \text{Eq. 6}$$

where $CF_{WE,\, k}$ is the work environment characterization factor for the years lost due to occupational accidents in the production of output k [e.g. years/kWh electricity] and m_k is the output of k [e.g. kWh electricity]. Industry-level work environment characterization factors from Scanlon et al. (2014), which are based on US health and safety data and related quantities of industrial outputs, were applied for $CF_{WE,\, k}$. The data presented in Section 3.1.1 was applied for m_k and then the main flows were followed in the background system for these inputs and outputs. The approach developed by Scanlon et al. (2014) is not implemented in the Ecoinvent database and thus not coupled to its inventory data. Therefore, the approach had to be applied in a less comprehensive way compared to the calculations of human health impacts associated with production system emissions described in Section 3.2.1. Only occupational accidents associated with the main flows in the production system for large-scale mining and processing were assessed in order to make the assessment feasible while still aiming at capturing the largest contributions to occupational human health impacts. The main flows included in the assessment, the Ecoinvent processes used to follow these main flows and the type of work environment characterization factors applied are presented in Figure A1 and Table A4 in the Appendix. When it comes to the modelling of occupational accidents due to the use and generation of electricity, data on what shares of the electricity production globally that is generated by various energy sources, e.g. coal and hydro, from IEA (2020) was applied.

3.2.3 Occupational accidents in artisanal diamond mining and processing

Artisanal mining and processing activities tend to have very poor health and safety practices (IGF, 2017) and the working conditions in artisanal mining in the DRC are exceedingly dangerous (World Bank, 2008). Human health impacts due to occupational accidents in artisanal diamond mining and processing were not assessed applying data from Scanlon et al. (2014). This was since their work environment characterization factors are based on US industrial health and safety data, which were not expected to adequately represent artisanal mining and processing activities. Instead, the years lost per carat diamond from artisanal mining and processing in the DRC ($DALY_{occ\ acc\ am}$) were quantified according to:

$$\mathrm{DALY_{occ\ acc\ am}} = (\mathrm{DALY_{fatal\ acc}} + \mathrm{DALY_{non\text{-}fatal\ acc}}) / \mathrm{m_{diamond\ DRC}} \qquad \text{Eq. 7}$$

$$\mathrm{DALY_{fatal\ acc}} = \mathrm{N_{miners}} \times f \times \left(s_c \times \left(L_{LEX} - L_{death,\ c}\right) + (1-s_c) \times \left(L_{LEX} - L_{death,\ a}\right)\right) \qquad \text{Eq. 8}$$

$$\mathrm{DALY_{non\text{-}fatal\ acc}} = \mathrm{N_{miners}} \times \sum_{p} I_{A,\ p} \times D_{W,\ p} \times L_{D,\ p} \qquad \text{Eq. 9}$$

where $DALY_{fatal\ acc}$ is the years lost due to fatal accidents in artisanal diamond mining in the DRC [year], $DALY_{non\text{-}fatal\ acc}$ is the years lost due to non-fatal accidents in artisanal diamond mining in the DRC [year], $m_{diamond\ DRC}$ is the amount of artisanal diamond mined in the DRC [carat], N_{miners} is the number of artisanal diamond miners in the DRC [-], f is the annual fatal accident rate for artisanal diamond miners [-], s_c is the share of artisanal diamond miners in the DRC that are children [-], L_{LEX} is the life expectancy in the DRC [year], $L_{death,c}$ is the age at death for artisanal miners in the DRC that are children [year],], $L_{death,a}$ is the age at death for artisanal miners in the DRC that are adults [year], $I_{A,\ p}$ is the number of incidences for accident p [-], $D_{W,\ p}$ is the disability weight for accident p [-] and $L_{D,\ p}$ is the time spent with disability p until recovery or death [year].

Data from various sources were utilized for the calculations. The amount natural diamond that was mined in the DRC in 2016 was set to about 23 million carats based on USGS (2020). The World Bank (2008) estimated that there are 0.7-1 million artisanal natural diamond miners in the DRC, and the average value of 0.85 million miners was applied as the baseline value in this study. The annual fatal accident rate of artisanal miners in general have been reported to be 2.5% by the ILO (1999). Furthermore, fatalities to artisanal miners operating in one cobalt mine in the DRC in 2006, which corresponds to an annual fatal accident rate at 0.4-0.5% of the workforce, have been reported (Tsurukawa et al., 2011). However, Tsurukawa et al. (2011) stated that the potential representativeness of these figures for the current artisanal mining sector is in need of being investigated. Due to limited data, an annual fatal accident rate at 1.5% was applied as the baseline value in this study for artisanal diamond mining, and the range of 0.4-2.5% was tested in the sensitivity analysis.

The life expectancy at birth in the DRC were about 60 years in 2016 (World Bank, 2020). When it comes to the age of miners, both children and adults work in the diamond mines. Child labor, mainly in the form of artisanal mining of for example diamonds, has been highlighted for its prevalence in the DRC (US DoL, 2020). It has been estimated that as much as 40% of the artisanal miners in the DRC are children (World Bank, 2008). This general figure was used for artisanal diamond mining, specifically, and the age of these children was set to vary between 5-17 years based on ILO (2005) and O'Driscoll (2017). The remainder, i.e. the rest 60% of the miners, were assumed to be adults older than 17 years. In 2009, Elenge et al. (2013) conducted a survey of artisanal mining in Katanga in the DRC and stated that the age of artisanal miners in their survey varied between 19-37 years. This data, which reflected 90% of the miners in the survey by Elenge et al. (2013), was applied for the age of adult artisanal diamond miners in this study. Furthermore, Elenge et al. (2013) provided statistical data on accidents in the artisanal mining sector of the DRC. On average in a year, a miner had 2.2 accidents of which 5.4% and 44.4% of the accidents were reported to cause fractures and wounds, respectively. Based on this, the average annual number of accidents per artisanal miner that resulted in fractures and wounds were calculated at about 0.12 and 0.98, respectively. Disability weights of 0.01–0.4 and 0.006 for fractures and wounds, respectively, were used (Salomon et al., 2015). The time spent with a disability until recovery was set to one to six months for fractures (MEDIBAS, 2018) and assumed to be one to four weeks for wounds.

3.2.4 Conflict diamonds

The fact that the mining and trade of minerals are financing civil warfare and conflict in the DRC have gained attention internationally, for example through the introduction of the Dodd-Frank act (Young, 2015). This act defines tin, tantalum, tungsten and gold as conflict minerals. However, diamonds have also been associated with this conflict. Conflict diamonds are essentially diamonds originating from artisanal mining in weak states, where impoverished and informal miners fall prey to armed groups (Vlassenroot and Van Bockstael, 2008). This is for example the case of diamond mining in countries such as the DRC, where 100% of the natural diamond mining is artisanal (Van Bockstael, 2018). In order to include conflict-related human health impacts of artisanal diamond mining in the DRC, data on the number of years lost per kg of mined diamond provided by Furberg et al. (2018b) were utilized. Note that only premature direct deaths, and not cases of disability or indirect impacts, were included in the figures provided from that study. Thus, conflict-related human health impacts of artisanal diamond mining in the DRC, limited to premature deaths, in terms of years lost per carat diamond ($DALY_{conflict}$), was calculated according to:

$$DALY_{conflict} = CF_{diamond} \times M_{diamond\ DRC} / m_{diamond\ DRC} \qquad \text{Eq. 10}$$

where $CF_{diamond}$ is the number of years lost per kg diamond mined in the DRC [year/kg], $M_{diamond\ DRC}$ is the total amount of artisanal diamond production in the DRC [kg] and $m_{diamond\ DRC}$ is again the amount of artisanal diamond that is produced in the DRC [carat]. Note that one carat equals 0.2 gram and that $CF_{diamond}$, which reflects conflict-related impacts, was obtained from Furberg et al. (2018b), applying their inclusive scenario, where a large number of conflict minerals were considered (tin, tantalum, tungsten, gold, copper, cobalt and diamond). The base case value for $CF_{diamond}$ from Furberg et al. (2018b) was applied as the baseline value in this study while their low and high values were applied in the sensitivity analysis.

4 Results

4.1 Environmental impacts of global diamond production

Results for environmental impacts per functional unit are presented in Table 1. Note that a limited number of inputs and outputs were included in the assessment and that environmental impacts of artisanal mining were excluded in this screening study. The results for one carat diamond from large-scale mining and processing, which has not been scaled as in Table 1 to be representative for the global production, are provided in Table A5 in the Appendix.

Table 1. Environmental impact results per functional unit, i.e. 1 carat natural diamond produced globally, applying baseline values. Values are rounded to two significant figures

Impact category	Value	Unit
Climate change	29	kg CO2 eq/carat
Terrestrial acidification	0.10	kg SO2 eq/carat
Freshwater eutrophication	0.013	kg P eq/carat
Stratospheric ozone depletion	$1.4 \cdot 10^{-5}$	kg CFC11 eq/carat

The input of electricity to large-scale diamond mining and processing contributes with about 80-99% to all impact categories shown in Table 1, while the use of diesel essentially contributes with the remainder. The landfilling of tailings did not contribute significantly to any of the included impact categories in this study.

4.2 Human health impacts of global diamond production

The human health impact per functional unit is about 1.3 days/carat. Thus, considering that the global production of natural diamond was 134 million carat in 2016 (USGS, 2020), the annual global natural diamond production is responsible for the loss of about 490 000 life years. Note that the functional unit applied here, i.e. one carat natural diamond produced globally, represents about 0.83 carat from large-scale diamond mining and processing and 0.17 carat from artisanal mining and processing in the DRC. The different contributions to human health impacts of global natural diamond production are illustrated in Figure 3. Furthermore, the results for the different human health impact contributions, which has not been scaled to be representative for the global production, are provided in Table A6 in the Appendix.

In 2016, artisanal diamond mining and processing of diamond in the DRC was responsible for almost one fifth of the global natural diamond production (USGS, 2020). Figure 3 shows that occupational accidents in artisanal diamond mining and processing in the DRC clearly dominate the human health impacts of global natural diamond production at 97%. Years lost due to premature deaths and years lost due to disability contribute with about 99% and 1% to this impact, respectively. The second largest contributor to human health impacts in global natural diamond production is from production system emissions in large-scale diamond mining and processing at 2%. Fine particulate matter formation and climate change are responsible for about 53% and 35% of this impact, respectively. Human health impacts related to occupational accidents in the production system of large-scale diamond mining and processing and related to the mining of conflict diamond only contribute with about 0.64% and 0.26% to the total impact, respectively (Figure 3).

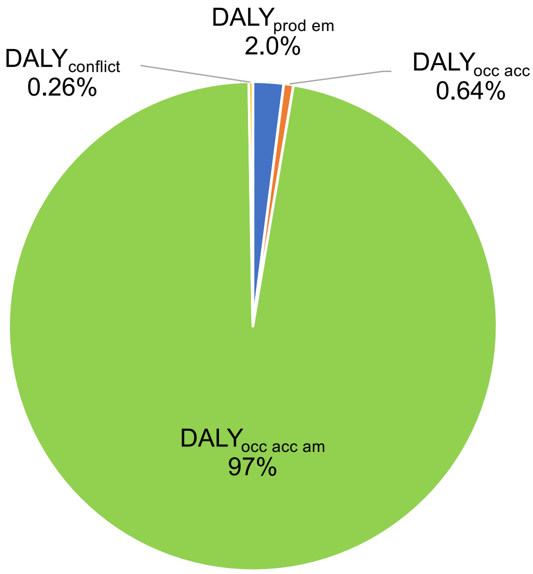

Figure 3. The share of different contributions to human health impacts per functional unit of 1 carat natural diamond produced globally. The total impact, quantified by the application of the disability-adjusted life years (DALY) indicator, is 1.3 days/carat. $DALY_{prod\ em}$ = years lost due to emissions in the product system of large-scale natural diamond mining and processing, $DALY_{occ\ acc}$ = years lost due to occupational accidents in the production system of large-scale diamond mining and processing, $DALY_{occ\ acc\ am}$ = years lost due to occupational accidents in artisanal diamond mining and processing in the Democratic Republic of the Congo (DRC) and $DALY_{conflict}$ = the years lost due to conflict-related fatal accidents in artisanal mining in the DRC. Values are presented with two significant figures

4.3 Sensitivity analysis

The sensitivity analysis identified a number of parameters as sensitive. Parameters that caused changes in environmental and human health impact results with more than 10% relative to when baseline values were applied are presented in Table 2. For environmental impacts, only changes in the electricity consumption for large-scale diamond mining and processing resulted in >10% differences. Furthermore, these differences were identified for all the impact categories included in this study. For human health impacts, changes in several parameters related to the situation in the artisanal diamond mining and processing in the DRC result in >10% differences in health impacts. The parameter for which changes cause the largest differences in human health impact results is the annual fatal accident rate, implying that a reduction in the accident rate of artisanal mining workers could reduce human health impacts considerably.

Table 2. Sensitivity analysis results for environmental and human health impacts. Only parameters causing changes in the resulting values for environmental impacts and human health impacts that were larger than 10% relative to when the baseline values were applied are presented. Values are presented with two significant figures. CC=climate change, FE=freshwater eutrophication, TE=terrestrial acidification, SOD=stratospheric ozone depletion, DRC=the Democratic Republic of the Congo

Parameter	Low value	High value
Environmental impacts		
Electricity consumption	- 79% CC - 73% TA - 82% FE - 67% SOD	+ 79% CC + 73% TA + 82% FE + 67% SOD
Human health impacts		
Amount of natural diamond mined in the DRC	+ 47%	0%
Number of artisanal diamond miners in the DRC	- 17%	+ 17%
Annual fatal accident rate	- 69%	+ 69%
Age of artisanal miners - adults	+ 13%	- 13%

5 Concluding discussion

This screening LCA presents results for the environmental and human health impacts associated with the production of rough natural diamond globally. The human health impact results for the annual global natural diamond production, which was 134 million carats in 2016 (USGS, 2020), show a loss of about 490 000 life years. The results for human health impacts furthermore show that the contribution from occupational accidents in artisanal mining and processing to the total human health impacts of one carat diamond is substantial. About one fifth of the global natural diamond production comes from artisanal mining and processing. However, the occupational human health impacts associated with artisanal mining and processing contribute with 97% of the total human health impact at 1.3 days per carat. Thus, in order to reduce the human health impact associated with natural diamond, safer working situations for artisanal miners should be given priority. Other contributions assessed in this study include impacts from emissions and occupational accidents in the production system of large-scale mining and processing as well as impacts from the mining of conflict diamond. Together, these other contributions are only responsible for a few percentages of the total human health impact. Contrary, environmental impacts in terms of climate change, freshwater eutrophication, terrestrial acidification and stratospheric ozone depletion were clearly dominated by the use of electricity in large-scale mining and processing. The results provided from this study can be applied in future LCAs of natural diamond and products containing natural diamond.

There are several examples of aspects that are in need of being considered in future studies of natural diamond. First, issues with obtaining reliable and up-to-date data for artisanal mining should be acknowledged. According to the World Bank (2019), accurate and reliable data that portray artisanal and small-scale mining activities in geographies such as Sub-Saharan Africa are rare. For example, the amount of diamond produced in the DRC is uncertain since all diamonds mined do not become declared to authorities (World Bank, 2008). Reliable statistics on occupational accidents in artisanal mining is also difficult to obtain. This is for example due to that studies, such as the one by Elenge et al. (2013), which present statistics based on surveys among miners, only represents the miners that were so healthy that they were able to go to work. Thus, more severe accidents, including fatalities, are not easily covered in these types of surveys. The sensitivity analysis conducted in this study identified parameters such as the amount of natural diamond mined in the DRC, the number of artisanal diamond miners in the DRC and the annual fatal accident rate as being sensitive. While it should be acknowledged that it can be quite difficult to obtain reliable data for these parameters, it is important that future studies prioritize this since the values applied for these parameters clearly affect the results.

Second, the assessment of environmental impacts of natural diamond in this study was limited to consider large-scale mining and processing and further to the inclusion of the major inputs of electricity and fuel as well as the output of tailings. Future studies should aim at a more comprehensive assessment of large-scale diamond mining and processing. For example, this could be done by also including data on the use of materials in the dense-medium separation cyclones as well as on the use of acids and bases in the process of cleaning diamonds. In addition, environmental impacts in artisanal diamond mining and processing were not included in this study. Future studies of natural diamond should further investigate the potential significance of such impacts.

Third, this study only considered negative human health impacts, while for example positive human health impacts stemming from the fact that the mining of natural diamond provides income for artisanal miners has not been considered here. It has been estimated that for each artisanal miner, about 4-5 persons are indirectly affected since their livelihood depends on the activity of that miner (World Bank, 2008). While there does exist a method to consider positive human health impacts (Feschet et al., 2013), this method is limited to poor countries with low corruption. This implies that it is only valid for countries where the economic wealth is needed in order to improve the health situation and where this wealth becomes spread over the countries' economic sectors (i.e. not distributed unequally due to corruption). This method is, however, not applicable to the DRC since it is a country marked by a high level of corruption (Transparency International, 2019). Thus, the generated wealth from for example diamond mining most probably does not become spread over the DRC's different economic sectors. The development of a new method for quantifying positive human health impacts in countries marked by high corruption is recommended.

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Appendix

Table of Contents

1 Data for calculations and sensitivity analysis

Table A1. Data for large-scale natural diamond mining and processing presented per carat rough natural diamond. Data are presented with two significant figures. Note that for the parameter marked with an asterisk (*), no value range was available from the reference, why the baseline value was decreased and increased with 50% to obtain low and high values, respectively, for the sensitivity analysis

Parameter [unit]	Baseline value	Comment	Sensitivity analysis		References
			Low value	High value	
Electricity consumption [kWh/carat]	44	The data variation stems from variation in the location of mines and the specific mining technology applied	7.5	80	Ali (2017)
Fuel use [kg diesel/carat]	3.6	The reference provided data in pounds/carat, which was recalculated into kg	1.9	5.2	Ali (2017)
Tailings [kg/carat]*	2 600	Rejected to landfill. Note that the amount of diamond ore mined approximately equals this amount	1 300	3 900	Marinescu et al. (2016)

Table A2. Data for artisanal natural diamond mining and processing and for conflict diamonds. Values are presented with two significant figures. Note that for parameters marked with an asterisk (*), no value range was available from the reference, why their baseline values were decreased and increased with 50% to obtain low and high values, respectively, for the sensitivity analysis. DRC = the Democratic Republic of the Congo

Parameter [unit]	Baseline value	Comment	Sensitivity analysis		References
			Low value	High value	
Amount of natural diamond mined in the DRC [million carats]	23	In 2016. Including both gemstone and industrial diamond quality. The low and high values were obtained by selecting the lowest and highest value for this amount in the time period of 2012-2016. Note that one carat equals 0.2 gram	16	23	USGS (2020)
Number of artisanal diamond miners in the DRC [million persons]	0.85	-	0.7	1	World Bank (2008)

Parameter [unit]	Baseline value	Comment	Sensitivity analysis		References
			Low value	High value	
Annual fatal accident rate [% of miners]	1.5	The low value represents one artisanal cobalt mine in the DRC, the high value represents artisanal mining in general	0.4	2.5	Tsurukawa et al. (2011), ILO (1999)
Life expectancy in the DRC [years]	60	In 2016. The low and high values were obtained by selecting the lowest and highest value for the life expectancy in the time period of 2014-2018	59	60	World Bank (2020)
Share of artisanal miners that are children in the DRC [%]*	40	-	20	60	World Bank (2008)
Age of artisanal miners - adults [years]	28	Artisanal miners in the DRC	19	37	Elenge et al. (2013)
Age of artisanal miners - children [years]	11	General figure for artisanal mining	5	17	ILO (2005), O'Driscoll (2017)
Number of incidences of accidents resulting in wounds per miner in a year [-]*	0.98	Baseline values were obtained by multiplying the annual average number of accidents per miner (2.2) with the fraction of these accidents that were fractures (5.4%) or wounds (44.4%)	0.49	1.5	Elenge et al. (2013)
Number of incidences of accidents resulting in fractures per miner in a year [-]*	0.12		0.059	0.18	
Disability weight for fractures [-]	0.21	-	0.01	0.4	Salomon et al. (2015)
Disability weight for wounds [-]*	0.006	-	0.003	0.009	
Time spent with fractures until recovery [years]	0.29	-	0.083	0.5	MEDIBAS (2018)
Time spent with wounds until recovery [years]	0.052	-	0.021	0.083	Assumption by the author
Characterization factor for the conflict mineral of diamond [year/kg]	0.28	Applying the inclusive scenario from the reference	0.17	0.34	Furberg et al. (2018b)

2 Background system modelling

Table A3. Ecoinvent processes applied for the background system modelling of large-scale mining and processing (Ecoinvent database version 3.7, 2020)

Input or output	Ecoinvent process
Diesel	market group for diesel | diesel | Cutoff, U - GLO
Electricity	market group for electricity, low voltage | electricity, low voltage | Cutoff, U – GLO
Tailings	market for non-sulfidic tailing, off-site | non-sulfidic tailing, off-site | Cutoff, U – GLO

3 Data for occupational accidents in large-scale mining and processing

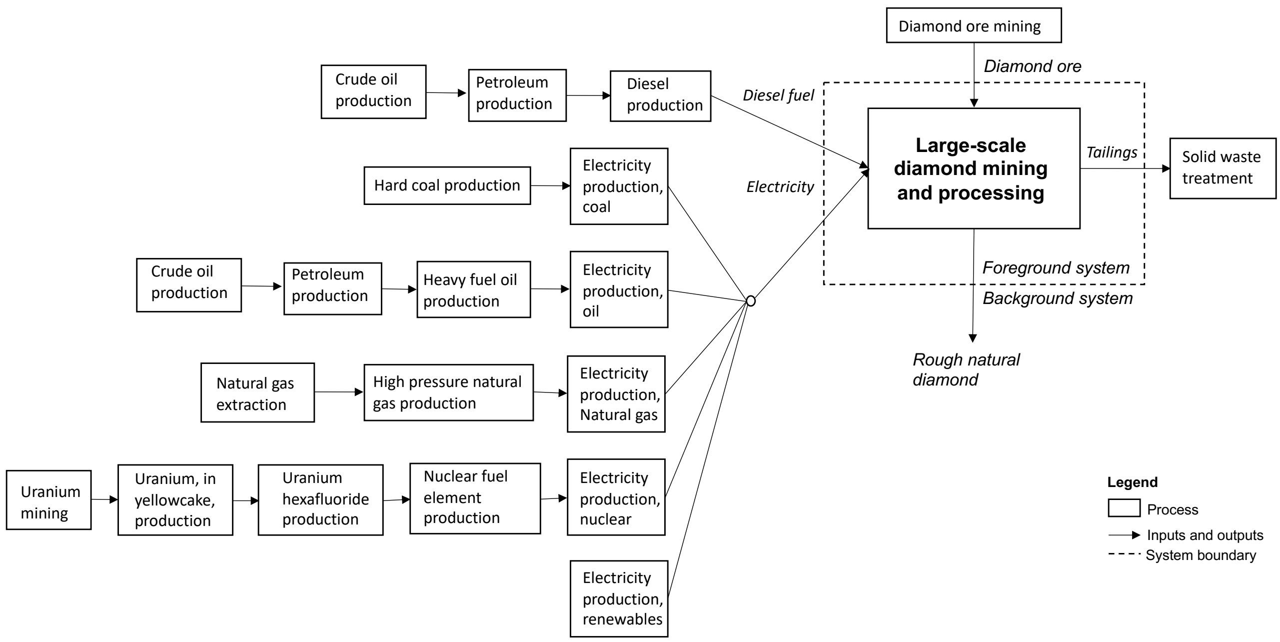

Figure A1. Flowchart for the included foreground and background processes in the quantification of life cycle occupational accidents in large-scale mining and processing

Table A4. Presentation of the inputs and outputs in the foreground and background system included in the quantification of occupational accidents in large-scale mining and processing. The Ecoinvent processes applied to follow main flows in the background system and the type of work environment characterization factors applied, the latter identified by their industrial categories, are also presented

Product	Ecoinvent process (Ecoinvent database version 3.7, 2020)	Industrial category (Scanlon et al., 2014)
Crude oil	-	211111 Crude Petroleum and Natural Gas Extraction
Diamond ore	-	212399 All Other Nonmetallic Mineral Mining
Diesel	Diesel production, petroleum refinery operation | diesel | Cutoff, U - RoW	325110 Petrochemical Manufacturing
Electricity, coal	Electricity production, hard coal | electricity, high voltage | Cutoff, U - RoW	221112 Fossil Fuel Electric Power Generation
Electricity, natural gas	Electricity production, natural gas, conventional power plant | electricity, high voltage | Cutoff, U - RoW	221112 Fossil Fuel Electric Power Generation
Electricity, nuclear	Electricity production, nuclear, pressure water reactor | electricity, high voltage | Cutoff, U - Row	221119 Other Electric Power Generation
Electricity, oil	Electricity production, oil | electricity, high voltage | Cutoff, U - RoW	221112 Fossil Fuel Electric Power Generation
Electricity, renewables (hydro, geothermal/tidal/other, solar, wind, biofuels/waste)	-	221119 Other Electric Power Generation
Hard coal	-	212113 Anthracite Mining
Heavy fuel oil	Heavy fuel oil production, petroleum refinery operation | heavy fuel oil | Cutoff, U - RoW	325110 Petrochemical Manufacturing
Natural gas	-	211111 Crude Petroleum and Natural Gas Extraction
Natural gas, high pressure	Natural gas production | natural gas, high pressure | Cutoff, U - RoW	325120 Industrial Gas Manufacturing
Nuclear fuel element, for pressure water reactor	Nuclear fuel element production, for pressure water reactor, UO2 4.2% & MOX | nuclear fuel element, for pressure water reactor, UO2 4.2% & MOX | Cutoff, U - RoW	325188 All Other Basic Inorganic Chemical Manufacturing
Petroleum	Petroleum production, onshore | petroleum | Cutoff, U - RoW	324110 Petroleum Refineries
Tailings	-	562212 Solid Waste Landfill
Uranium, enriched 4.2%, in fuel element for light water reactor	Uranium fuel element production, enriched 4.2%, for light water reactor | uranium, enriched 4.2%, in fuel element for light water reactor | Cutoff, U- RoW	-
Uranium, enriched 4.2%, per separative work unit	Uranium production, centrifuge, enriched 4.2% | uranium, enriched 4.2%, per separative work unit | Cutoff, U - RoW	-

Product	Ecoinvent process (Ecoinvent database version 3.7, 2020)	Industrial category (Scanlon et al., 2014)
Uranium hexafluoride	Uranium hexafluoride production | uranium hexafluoride | Cutoff, U - RoW	325188 All Other Basic Inorganic Chemical Manufacturing
Uranium in ore	-	212291 Uranium-Radium-Vanadium Ore Mining
Uranium, in yellowcake	Uranium production, in yellowcake | uranium, in yellowcake | Cutoff, U – RoW	325188 All Other Basic Inorganic Chemical Manufacturing

4 Environmental impact results for large-scale mining and processing

Table A5. Environmental impact results for large-scale natural diamond mining and processing applying baseline values. Values are rounded to two significant figures

Impact category [unit]	Value	Contribution analysis
Climate change [kg CO2 eq/carat]	35	95% market group for electricity, 5% market group for diesel
Terrestrial acidification [kg SO2 eq/carat]	0.12	88% market group for electricity, 12% market group for diesel
Freshwater eutrophication [kg P eq/carat]	0.016	99% market group for electricity, 1% market group for diesel
Stratospheric ozone depletion [kg CFC11 eq/carat]	$1.6 \cdot 10^{-5}$	80% market group for electricity, 20% market group for diesel

5 Human health impact result contributions

Table A6. Results for human health impacts associated with production system emissions in large-scale mining and processing ($DALY_{prod\ em}$), occupational accidents in the life cycle of large-scale diamond mining and processing ($DALY_{occ\ acc}$), occupational accidents in artisanal mining and processing of diamond in the Democratic Republic of the Congo (DRC) ($DALY_{occ\ acc\ am}$) and fatalities related to artisanal mining and processing of conflict diamonds in the DRC ($DALY_{conflict}$) applying baseline values. Values are rounded to two significant figures

Human health impact	Value	Unit
$DALY_{prod\ em}$	$9.1 \cdot 10^{-5}$	year/carat diamond from large-scale diamond mining and processing
$DALY_{occ\ acc}$	$2.85 \cdot 10^{-5}$	year/carat diamond from large-scale diamond mining and processing
$DALY_{occ\ acc\ am}$	0.021	year/carat diamond from artisanal mining and processing in the DRC
$DALY_{conflict}$	$5.6 \cdot 10^{-5}$	year/carat diamond from artisanal mining and processing in the DRC

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